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VIBRATIONAL MOTION OF ARCTIC PACK ICE

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Abstract

There are many physical mechanisms reasponsible for vibrations of sea, and they force motions in a very wide band of frequencies from less than 0.01 Hz to greater than 100 Hz. Detailed measurements of the vertical velocity in this frequency band were previously shown to be produced by gravity waves, ridging events and wind turbulence. In this paper, higher frequency motions as measured by geophones for frequencies up to about 1 kHz have been analyzed, and the motions are identified as being generated by ridging events, thermal fracturing, and wind blown ice crystals. The sensors were frozen into the top surface of the ice, and they provided direct measurements of the vertical velocity that occurs in response to the different modes of waves that propagate away from these generation regions. The shape of the frequency spectrum is shown to be a strong function of the forcing mechanism, with the different ones being readily identifiable.

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Introduction

Measurements of sea ice vibrations have been made with geophones and accelerometers at a high Arctic ice camp north of Fram Strait. These data were analyzed previously for the spectral shape and the probability distribution of spectral level in the frequency band from 10^{-2} - 10^{2} Hz, and this enabled the unique identification of several physical processess that accounted for most of the variance in the energy levels (Dugan *et al* 1992). Specifically, the identified processes included low-frequency swell that came through Fram Strait from the North Atlantic, motions due to turbulence in the local atmospheric boundary layer, and flexural waves due to ridging events at the floe boundary. The wind turbulence mechanism was a newly discovered one for causing ice motions, and a theoretical model was developed that incorporated forcing by pressure fluctuations associated with turbulent eddies in the atmospheric boundary layer (DiMarco *et al* 1991). Model predictions were favorably compared with measurements that were made for this specific purpose in cooperation with US Army Cold Regions Research and Engineering Laboratory (CRREL) personnel on a frozen lake in New Hampshire. Also, in conjunction with CRREL, a comparison was made of multi-year sea ice thickness measurements by drilling and by submarine acoustic remote sensing (Dugan *et al* 1989) and of the flexural rigidity parameter of sea ice as determined by the observed dispersion relation of flexural waves and as determined by the traditional coring method (DiMarco *et al* 1993). These results have contributed directly to our knowledge concerning the propagation of waves in sea ice, and they contributed to a review on the topic (Squire *et al* 1995).

The latter review is the result of a small but continuing effort by an international group of researchers that is investigating sea ice motions, including vibrations. In autumn of 1991, Peter Wadhams organized an IAPSO-sponsored workshop on the subject at the Scott Polar Research Institute of Cambridge University in the UK. This meeting of experts summarized the present state of knowledge and the outstanding problems regarding sea ice vibrations (Dugan 1991, Wadhams *et al* 1992, Squire *et al* 1995). It was recognized that Dugan *et al* (1992) set a new standard in establishing reliable estimates of the spectral levels and identifying the processes that were responsible for the ambient vibrations of ice on both first-year and multi-year floes. However, there have been numerous anomalous events in past observations, and an outstanding problem continues to be the identification of additional mechanisms that are responsible for these events. The frequency band in which Dugan *et al* (1992) established nominal motion levels did not include internal gravity waves that are known to occur on lower frequencies, nor did it include acoustic vibrations that are known to occur at higher frequencies. Wadhams and Squire and their students (Cambridge University), as well as Smirnov and his students (AARI in St. Petersburg), have focused on the lower frequency surface and internal wave motions, but a commonly

accepted level of motion in the internal wave band remains elusive since most measurements have been sensor noise limited. Further, there are known sources of acoustic noise in the water (Ganton and Milne 1965, Milne 1974), generated by mechanisms that also include vibrations of the ice, but none of these efforts made direct measurements. These additional mechanisms include the noise of ice crystals being blown across the surface by the wind and the cracking that is caused by surface contraction which occurs mostly during periods of significant atmospheric cooling.

Nevertheless, even with these uncertainties, Dugan has proposed a model spectrum in the jointly written review paper of Squire *et al* (1995) for the nominal level of motion across the spectral band from 10^{-4} - 10^{3} Hz, based at least in part on quantitative inferences from the many different measurement systems used by the different institutions. A plot of the statistics of our vertical velocity spectra that was folded into the model spectrum is shown in Figure 1, and the different curves represent the 10%, 50% and 90% levels of the measured spectra of vertical velocity. Figure 2 is the inferred model spectra associated with the specific physical mechanisms that have been identified to present. Line A is the vertical velocity of internal gravity waves propagating in the halocline, as scaled from open ocean measurements of Pinkel (1975). Curve B is a model for surface gravity waves and is redrawn from Dugan *et al* (1992). Curve C is a model for wind turbulence-generated motions and is redrawn from Dugan *et al* (1992), while curve D is a theoretical prediction for motions due to turbulence in the near surface waterside boundary layer. Curve E is for flexural waves from pressure ridging and curve F is for acoustic waves in the ice, both redrawn from Dugan *et al* (1992). This figure is important primarily as a standard for comparison of other data sets, including any data that are collected in the future. However, there are a number of uncertainties in these results, and the situation for higher frequencies can be improved by analyses of the geophone data that were collected in our ice camp.

The primary objective of the work that is described here is to extend the model spectrum to higher frequency by including a description of additional mechanisms as determined by analysis of data from the same geophones that were examined previously in Dugan *et al* (1992). Thus, in the following, the results of analyses of geophone data are provided for frequencies higher than 100 Hz for the motions that are caused by the variously mentioned physical mechanisms. The next section summarizes the observations, and the following sections provide an overview of the analyses and, finally, our conclusions.

Ice Vibration Observations

In summary, several geophones were frozen into the surface of the ice on a multi-year floe in the high Arctic. These sensors measure the three components of velocity directly for frequencies above 8 Hz, and they were appropriately corrected for a sensor roll-off that occurs for frequencies below 8 Hz. The data were collected by two parallel recorders. The data for frequencies below 100 Hz were digitized in the field, analyzed for motions in the frequency band of 10^{-2} - 10^{2} Hz, and subsequently documented by Dugan *et al* (1992). In addition, a wider band of frequencies was recorded for two channels of the vertical component of velocity on a high-

quality audio/video cassette recorder having useful bandwidth between 20 Hz and 15 kHz. These data contain the signatures of high-energy motion events that extend to a frequency of at least 10^3 Hz, events that were unambiguously observed in the field to be associated with specific physical processes that occurred during our occupation of the ice camp. These observations include the noise of ice crystals that are blown across the surface by the wind, and individual ice cracking events that are caused by surface cooling and other unknown causes. Also, there is additional information that was not previously documented on the motions resulting from the several ridge-building events that were observed.

The wind is a dominant factor. When the wind speed is above a critical value of about 5 m/s, it picks up small ice crystals and blows them across the surface and, in doing so, causes an easily heard 'hissing' sound. This sound is a high frequency vibration (in the ice as well as in the air) that is caused by the nearly continuous collisions of the ice crystals as they are blown across the surface. It is these collisions that carve the hardened snow surface into the random but intricate designs of sastrugi. Although measured previously with hydrophones in the water by Ganton and Milne (1965) and Milne (1974) among others, there have been no documented, quantitative measurements of the vibrations in the ice. These vibrations were observed in our geophone measurements, and their spectral shape and energy level have been analyzed in conjunction with the mean wind speed. Figure 3 is a time series of the mean wind speed for an anemometer at 5 m height close to the ice camp. It shows several wind storms, and we have picked the time period of increasing wind during day 7 to illustrate this source of noise. Figure 4 shows several examples of the frequency spectrum for different wind speeds, and there is a distinct increase in level near 300 Hz for wind speeds above about 5 m/s. There was a low pass filter in a system pre-amplifier near the geophone that was set at 1.5 kHz, and this limited the response to frequencies below that value, so the calculated spectra have been cut off at 2 kHz. The spectral level is high for all winds above a threshold of about 5 m/s, as shown in Figure 5, which is a plot of the variance in a band from 400 Hz to 1.5 kHz versus the mean wind speed. There are several peaks in the spectra near 200 and 250 Hz and 1.0 and 1.4 kHz that move around somewhat in different time intervals, and they provide a distinct 'howl' to the sound. By sound, we mean the noise as heard by ear when the sensor signal was amplified and projected into the air with an audio speaker system. (We actually did this on a continuous basis for several of the sensors in the camp's science tent so that we had an audio clue as to what activity was occurring on the ice floe, and we have repeated the exercise in the laboratory while analyzing the data for this document.)

The most surprising result to us was the nearly discontinuous nature of the variance plot as a function of wind speed. The conclusion is that the vibration level of the ice surface in this narrow band is nearly independent of the specific wind speed, depending only on whether there are ice crystals in the air or not, as the threshold for their being airborne is about 5 m/s in these data. For our ice camp, this amounted to almost half the time, as shown by the horizontal line in Figure 3, and the resulting high noise level typically drowned out other sounds as measured by the geophones in the ice. The corresponding visual observation was that the crystals are blown along the surface in long, thin streamers associated with very strong wind-aligned vortices in the near-

surface boundary layer as they wind themselves along the rather rough sastrugi that was present almost everywhere on the frozen surface of the snow on our ice floe. This result is in stark contrast with the acoustic level that had been previously measured by hydrophones under the ice (Ganton and Milne 1965, Milne 1974), where the sound level was reported to be a strong but more linear function of the mean wind speed. On the other hand, the bandwidth of the noise is quite similar.

Also, the air temperature dropped sharply on several occasions during these geophone measurements, and this caused a considerable 'popping corn' noise of ice cracking due to contraction of the surface that was exposed to the air. This type of noise also has been observed and documented previously using hydrophones in the water by Ganton and Milne (1965), and Dyer (1983) has used these and his own observations to provide an interpretation of the mechanism responsible for the waterborne noise. This signal was buried in the wind noise on much of the data that we recorded, but there also were several isolated ice cracking events that were recorded with energy level well above other processes. Figure 6 is a time series of one of these cracking events, and Figure 7 is the frequency spectrum compared with the spectra of several other intervals of time which exhibited different phenomenology. This figure shows the response to be wide band, with a peak at 10 Hz or so, which is consistent with the model for the sound in the water presented by Dyer (1983). This spectrum is not unique in our data set, but we do not have a lot of unambiguous samples due to most of them being lower amplitude (smaller cracks and/or further away from the geophone), leading to their being submerged in the noise from other sources. You can hear the 'popcorn' in the audio data, but cannot easily detect it in the noise from other sources simply from its spectral shape and level.

Finally, there are events in our data where the noise level was elevated significantly by ridging along a boundary of the occupied ice floe. The vertical motions of the ice in the frequency band of 0.1-10 Hz were shown by Dugan *et al* (1992) to be dominated by motions that were consistent with the propagation of flexural waves in the ice. This also was a new result, as previous hydrophone measurements had identified a strong source of the noise as ridging events (eg., Pritchard 1984, Buck and Wilson 1986), but they had not identified the specific mode of propagation in the ice. The audio-recorded data were analyzed for a number of ridging events, and Figure 7 shows two typical spectra in the band from 10 Hz to more than 1 kHz. The lower of the two ridging examples is believed to be more distant, and it shows a level that falls off monotonically (except for the generator noise lines) from a peak near 10 Hz, but it also has peaks out near 1 kHz that are associated with wind noise. The more energetic of the two is thought to be a closer ridging event, and it also exhibits narrow-band peaks near 300 and 400 Hz. The peak near 1-10 Hz was identified by Dugan *et al* (1992), but the additional ones at several hundred Hz have been identified here for the first time. These secondary peaks almost certainly are due to a second mode of propagation of the vibrations in the ice. We know from our previous work that the peak near 1-10 Hz is due to flexural waves, and we speculate that this higher frequency one is due to other modes of elastic wave propagation in the ice and/or ice-water interface. Additional observations from a number of spectra of the ridging events are that these higher frequency peaks move around over short periods of time, and they only seem to appear in the higher energy

events. One possible conclusion that stems from the sometimes appearance of these secondary peaks is that their presence is dependent upon the distance to the source of noise, with the flexural waves decaying with distance at a lower rate than the higher frequency waves. Finally, Figure 8 is the spectrum averaged over longer time during a ridging event. and it more clearly shows the secondary peak centered near 50-100 Hz which appears smoother because it has benn averaged over the narrower ones as they move around in frequency.

Discussion and Conclusions

There are a number of interesting new results of these analyses, and the model spectrum exhibited in Squire *et al* (1995) is not as simple as explained therein. The spectral shape and levels of vertical velocity of the ice surface has been shown to depend upon the presence of specific noise generating events. The wind causes a high level of noise when the speed is greater than about 5 m/s for frequencies above about 300 Hz. The dependence of the noise level on the wind speed is very nonlinear near 5 m/s speed, and there is visual evidence that this is the threshold speed that is required to lift ice crystals from the surface and carry them around in the near-surface boundary layer. The result is in stark contrast with previously published noise measurements under the ice that show a much more linear level of noise with wind speed. Also, these present results exhibit much more structure in the spectrum than previously published in underwater acoustic noise spectra.

Also, the amplitude of nearby cracking events is very high, and the spectrum has a peak near 10 Hz which is near the peak of cracking events provided by Dyer (1983). We find that the level of this peak varies significantly, and this presumably is due to the closeness of the event to the geophone, as the more common cracking that occurred during surface cooling was often buried in the noise of other processes going on at the same time.

In addition, the noise of ridging events has been extended beyond the 100 Hz limit previously documented by Dugan *et al* (1992), and the spectra sometimes exhibit an additional peak in level in the vicinity of 100 Hz. The lower frequency peak near 1 Hz had previously been concluded to be due to flexural waves, and this additional one is speculated to be due to a second mode of propagation of elastic waves in the ice. We believe its absence or presence is due to the distance from the source of motions, with the higher frequency motions in the ice decaying with increasing distance faster than the lower frequency ones, but both peaks being generated by the ice cracking that occurs during the ridging events. This argument does not discount a possible second effect, which is the relative levels of the two motion types, with pressure ridging possibly generating larger vertical motions (that result in flexure of the ice) during the episodic compressive failure than the motions that would seem to occur during shear ridging events, but we do not have observations that can separate the two types.

These results and subsequent speculations lead us to suggest future experimentation in which geophones can be used to distinguish between the different generation and propagation

modes of the vibrations that likely result from the significantly different large scale motions in pressure and shear ridging.

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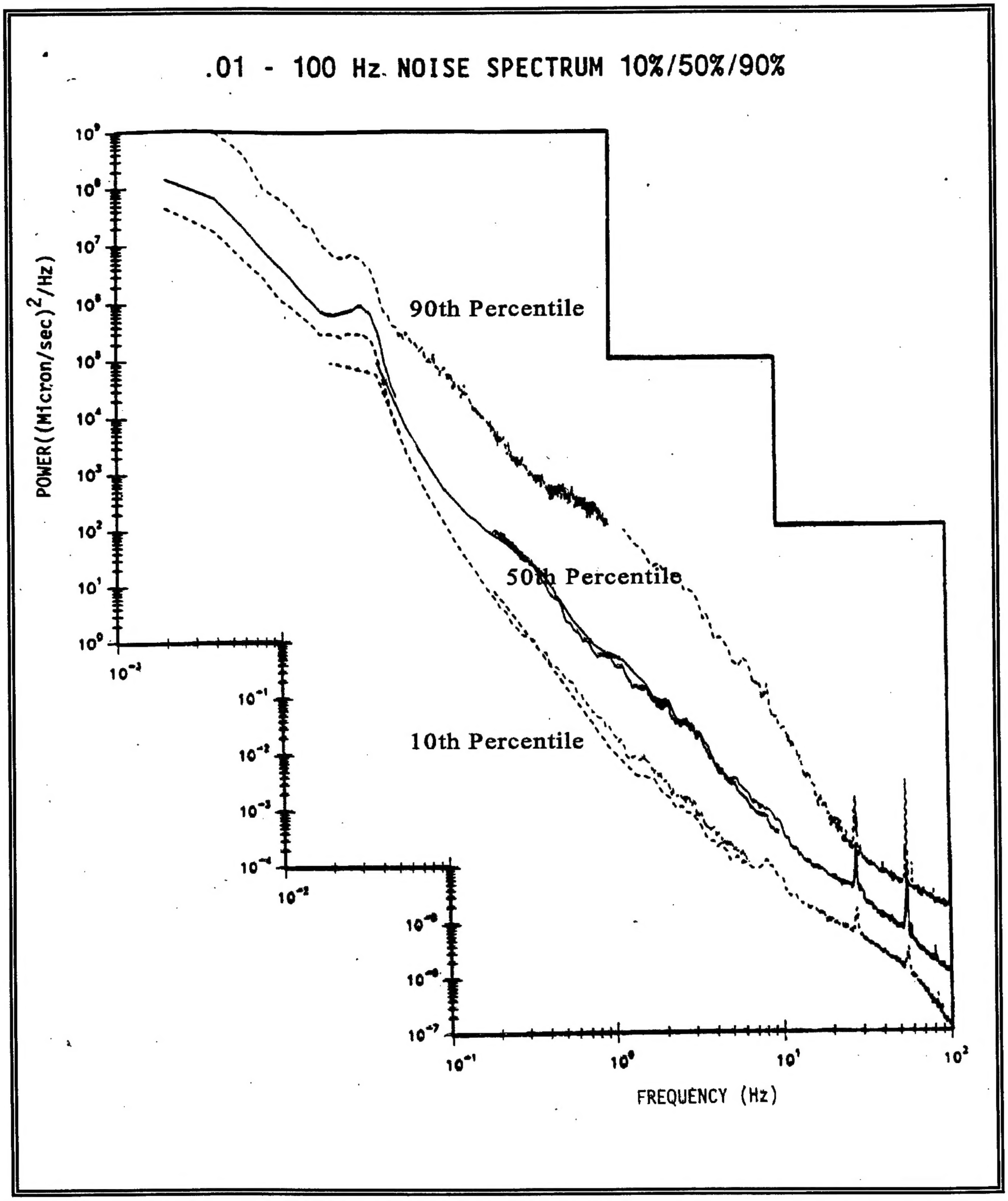

Figure 1. Lines represent the 10, 50, and 90 percentile of observed vertical velocity spectra on the multi-year pack ice, recalculated from the data in Dugan *et al* (1992). Data delow 0.3 Hz are from an accelerometer, while higher frequency data are from a geophone. The lines at 30 and 60 Hz are due to pickup from the camp generator.

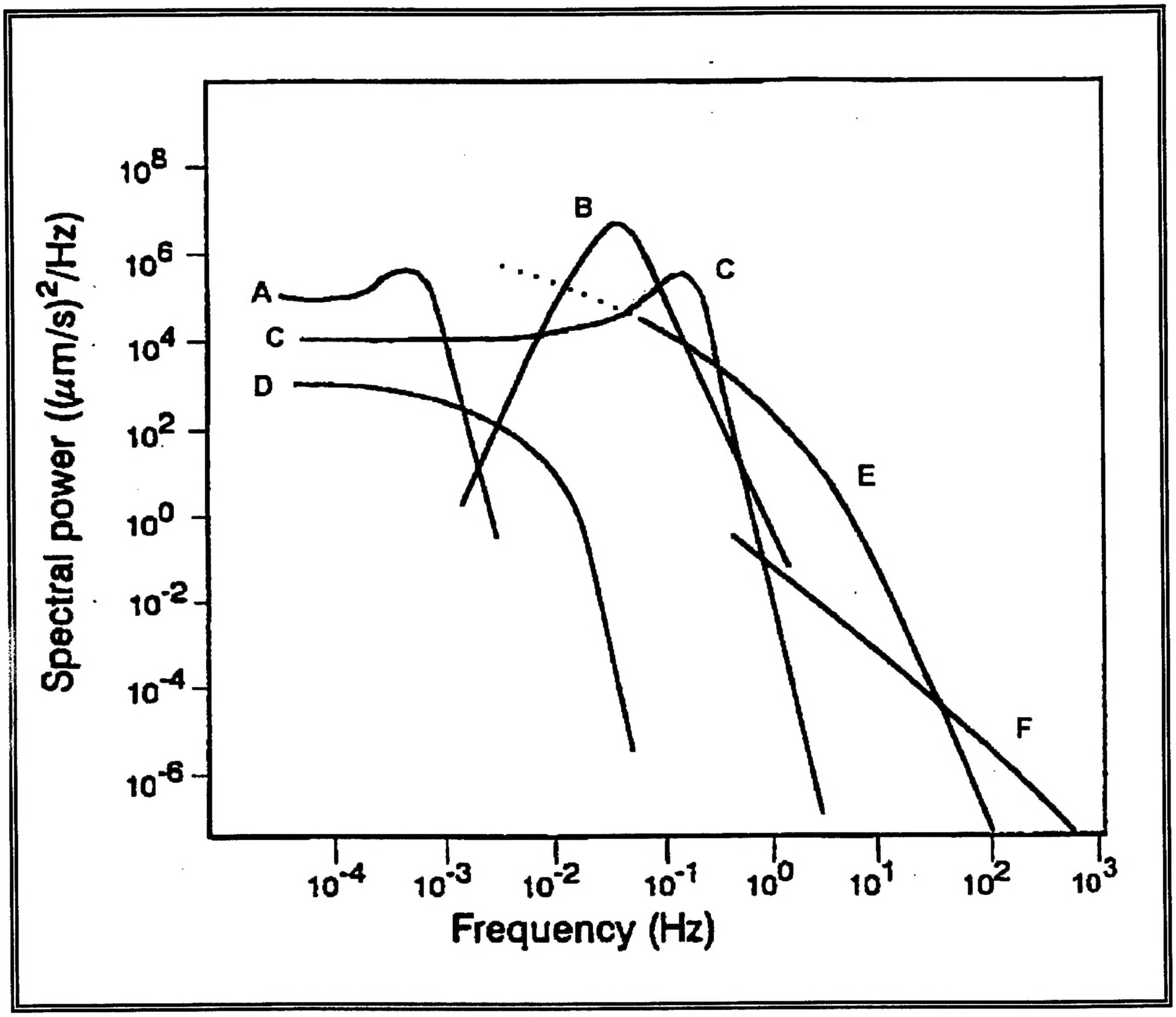

Figure 2. Model spectrum for vertical velocity of ice surface reproduced from Squire et al (1995) showing spectral levels and shapes for various ice vibration/motion processes. Specific ones explained in the text.

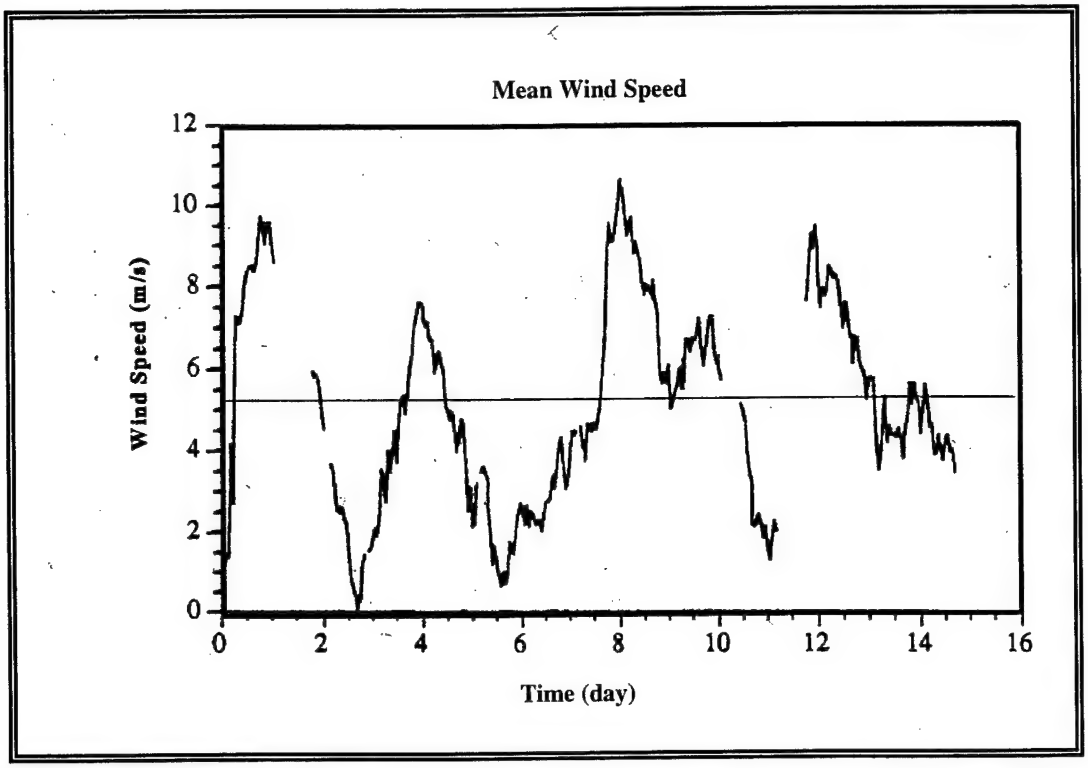

Figure 3. Mean wind speed for two week experiment period. Dotted line at 5.2 m/s is approximate threshold above which geophone observations were wind dominated.

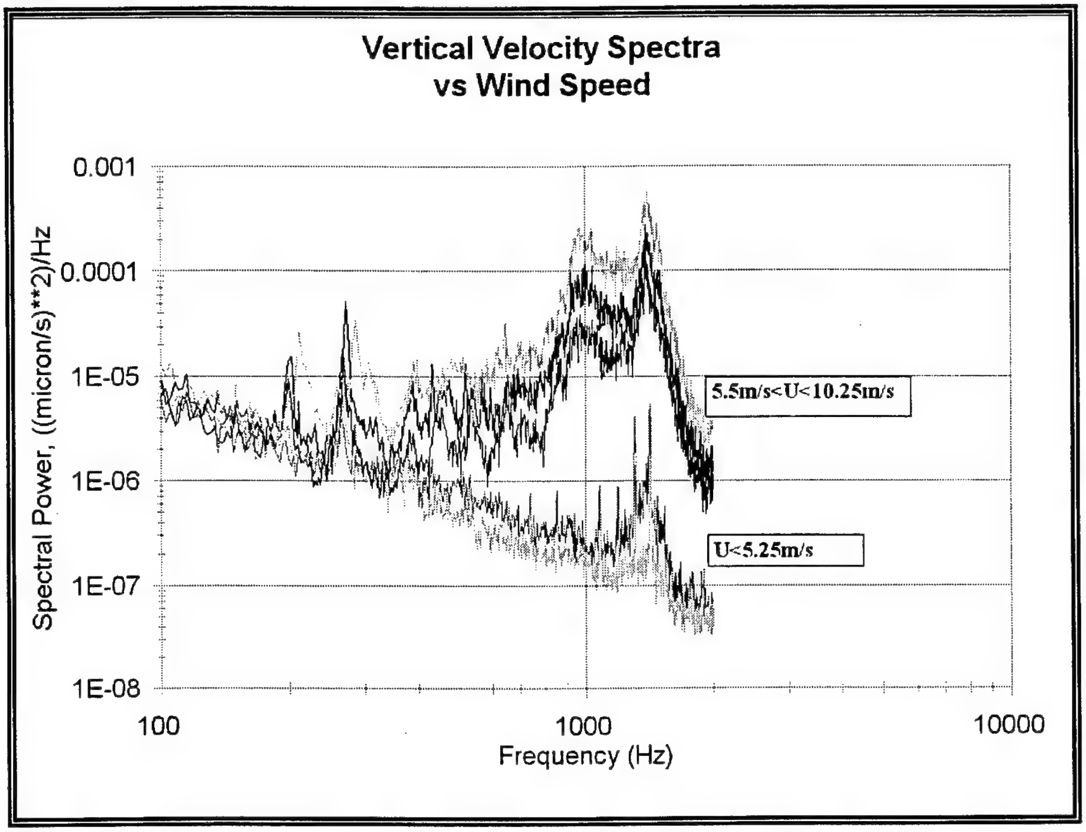

Figure 4. Frequency spectrum for several values of mean wind speed during a wind storm.

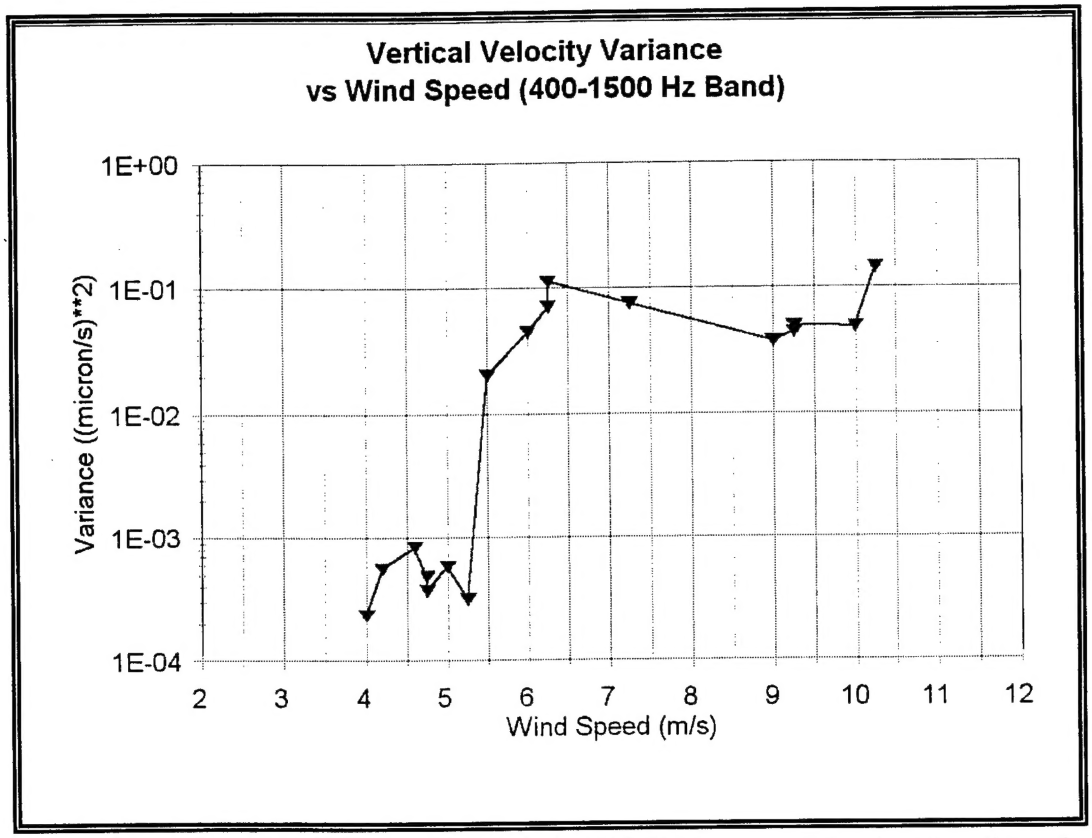

Figure 5. Vertical velocity variance in 400-1500 Hz frequency band as function of mean wind speed for one wind storm.

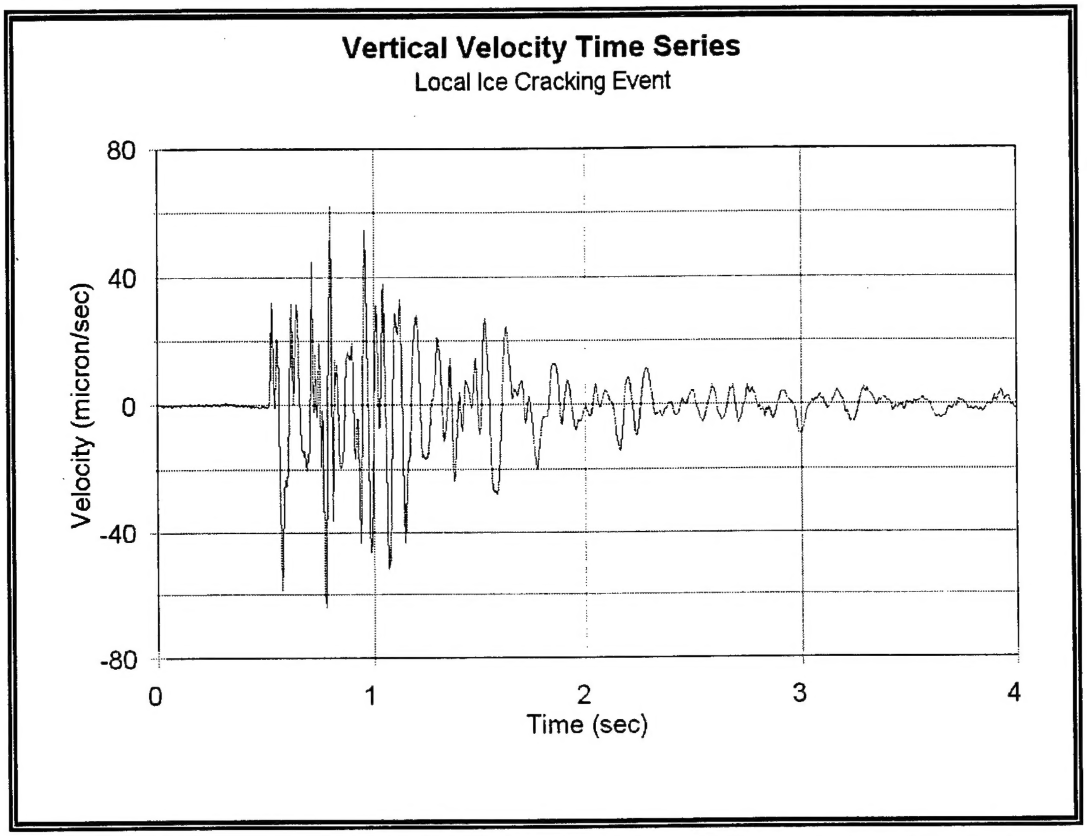

Figure 6. Time series of vertical velocity from ice cracking event nearby geophone.

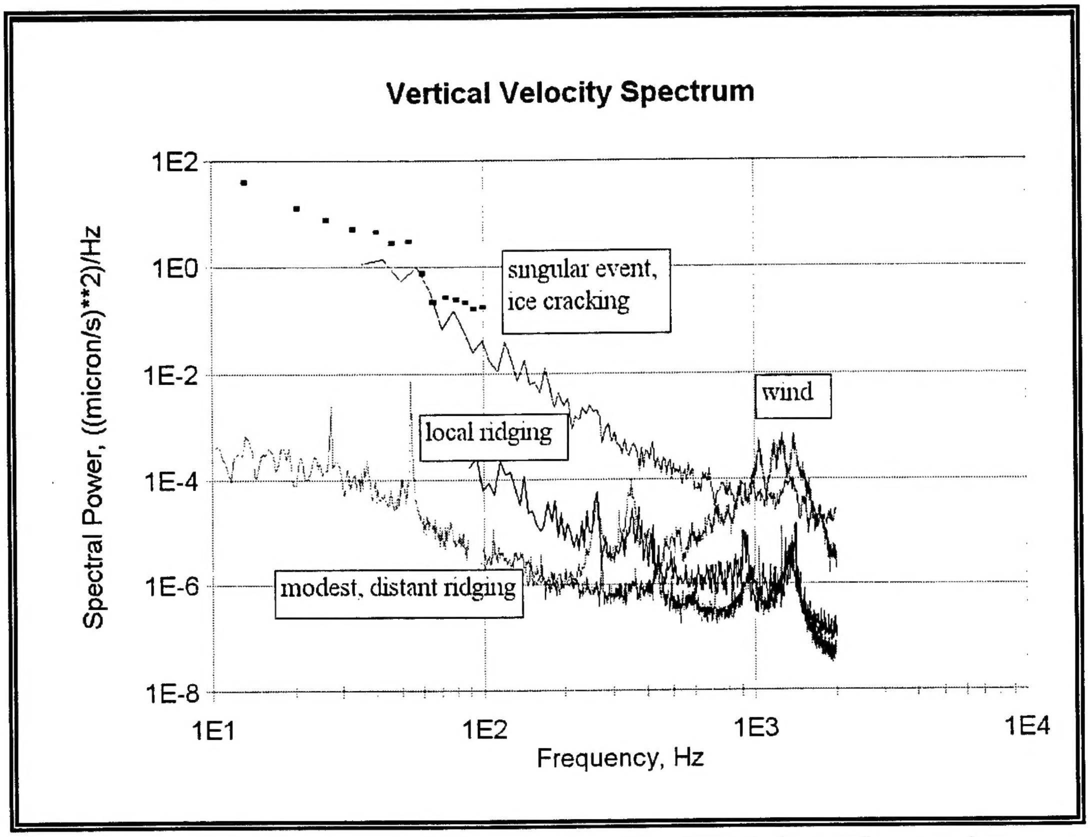

Figure 7. Composite spectra exhibiting spectral levels and shapes from various types of events on the ice. As before, data below 100 Hz from digital files discussed in Dugan *et al* (1992) and higher frequencies from data analyzed in this paper.

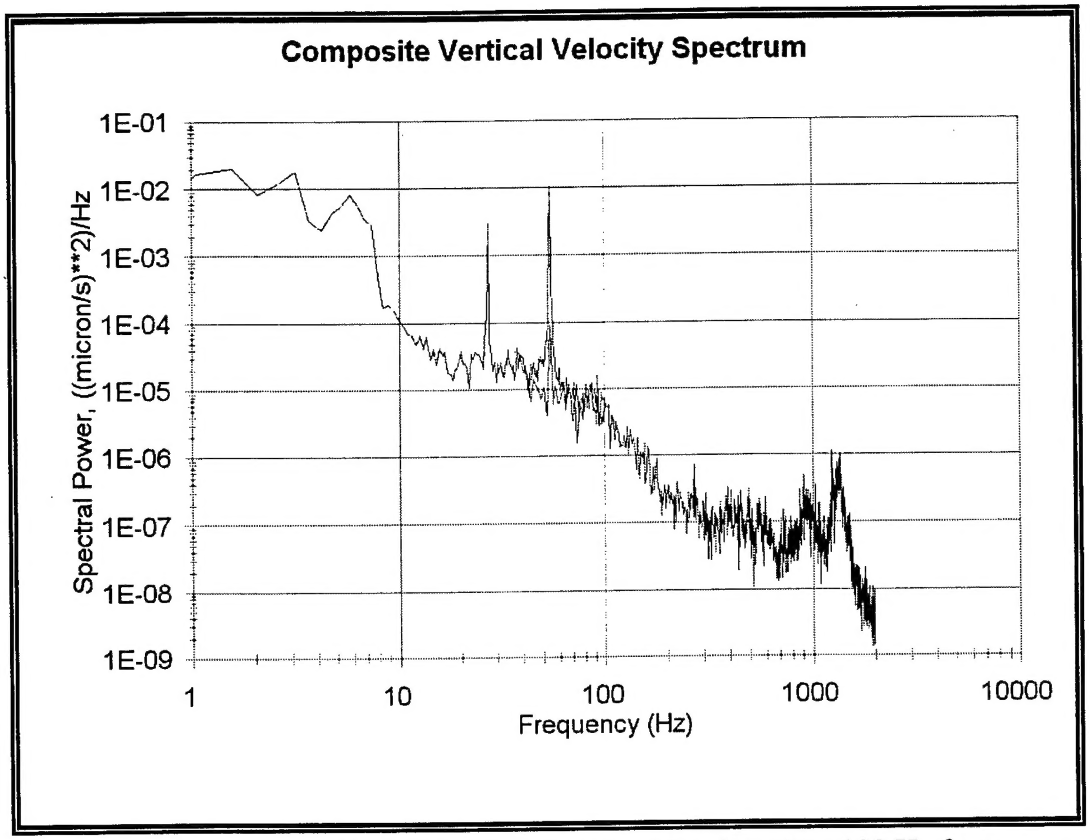

Figure 8. Composite vertical velocity spectrum -- data less than 100 Hz from digital data analyzed in Dugan et al (1992) and above 20 Hz from analysis in this paper, thus providing a comfortable overlap.